This paper presents an approach to network planning and engineering that addresses the issues described above. This approach has been implemented at Bellcore in the *Optiaccess* software system.* This paper describes both the planning and engineering approach and its implementation in software.

PLANNING AND ENGINEERING APPROACH

Figure 4 diagrams a new approach to local access planning and engineering systems. The approach features databases that fully parametrize descriptions of three categories of information. One database describes the subscriber and network sites in an area their geographic locations, and the interconnections between sites. Another database describes the services that are delivered to and collected from subscribers. This information includes several service attributes, such as bit rates or bandwidths in both the upstream (subscriber-to-network) and downstream (network-to-subscriber) directions, blocking probabilities, number of offered broadcast channels, and peak-hour demands and revenues for different categories of subscribers. The third database characterizes the equipment and facilities available to build the network. This database describes sizes of equipment and facilities, such as multiplexing ratios and cross-sections of cable, as well as costs, learning curve slopes, annual inflation rates, and performance attributes, such as attenuation and signal distortions.

These three categories of information are used to engineer and evaluate alternative networks. For a given choice of information for each of the three categories, the planning and engineering process can take account of the traffic demands, signal levels, numbers of subscribers served, and other independent variables at each point and for each facility section in a network. For each local access architecture supported by the planning and engineering system, rules can be applied that map these independent variables into the quantities of different pieces of equipment needed to meet the demands at each node. The fully engineered network can then be evaluated in terms of cost, by multiplying engineered quantities by unit costs, or in terms of other objective criteria such as cable cross-sections, signal levels, and so on.

The categories of information depicted on the left-hand side of Fig. 4 and the parameterization of the information in those categories makes it easy to model a large number of scenarios, varying any of the network planning attributes listed in Fig. 3. This approach makes it easy to study the sensitivities of network cost and other network objective functions with respect to variations in any of the inputs. It is also easy to derive optimal networks with respect to uncertainties or variations in any of these inputs.

EXTENSIBILITY

The next generation of planning and engineering tools must not only take into account current local access issues, but must also be able to evolve gracefully as new challenges arise. Some of these issues are listed in Fig. 5. Today, for example, there is a limited number of families of local access network architectures, including varieties of fiber-coax, fiber to the curb, and fiber to the home. In the future, however, additional architectures may be possible, taking advantage of new multiplexing techniques, new transmission media, advances in coding or compression techniques, or any other new technology. In addition, new planning and engineering tools should be able to incorporate changing visions of what services, take rates, and traffic demands new local access networks will support. They should be robust with respect to the numerous possible regulatory and business environments in which local access providers may operate in the future.

At present, local access architectures are often thought of in terms of a few key attributes, such as how far into the network fiber extends or what combination of transmission media or multiplexing techniques differentiate one architecture from another. To implement architectures in planning and engineering software, however, a more rigorous examination of the notion of an architecture is required. Fig. 6 explores this question.

One important aspect of a local access architecture is what services and traffic demands it can support. Clearly, a fiber-to-the-home architecture with high-speed electronics can support a greater set of services and a greater set of traffic demands than a simple copper loop network. For each architecture that might be implemented in a planning and engineering system, it is necessary to specify the service mixes for which the architecture is defined and how the architecture is able to support those services.

• The Optiacces system is currently available as a stand-alone system and work is underway at Bellcore aimed at incorporating it into other local acces planning and engineering tools.

The definition of an architecture must include a list of nodes in the network where functions are performed, a list of the equipment at each type of network and subscriber node, and a list of facilities linking network nodes. For example, a fiber-to-the-curb network might include four categories of nodes: subscribers, optical network units (ONUs), host digital terminals (HDTs), and central offices (COs). The planning tool will incorporate a list of equipment at each node type, such as transmitters and receivers at ONUs and HDTs and high-speed multiplexer and demultiplexers at HDTs and COs. There would also be a list of facilities linking different categories of nodes. Subscribers and ONUs would be linked with copper drop facilities, while fiber cables of a variety of sizes would link ONUs, HDTs, and COs.

Finally, a network architecture in a planning and engineering system must have deterministic algorithms for each type of network node. These algorithms map some set of independent variables, such as traffic handled, number of input cables, and equipment capacities, into the engineered quantities of equipment at a node and facilities connected to a node. The inputs to each algorithm, as well as the formulas relating engineered quantities to those inputs, will vary from one network approach to another and from one node type to another.

Figure 7 shows how new architectures can be incorporated into the planning and engineering system design approach shown in Fig. 4. The network evaluation part of the design approach consists of a set of architecture modules that run independently. Each architecture module engineers the portion of the network that is served by the corresponding architecture. In Fig. 7, the software would first engineer all sites and facilities serving subscribers by fiber-coax, then fiber to the curb, and then fiber to the home. It would then multiply engineered quantities for all architectures by unit costs and output engineering-and cost reports.

To add a new network architecture to this paradigm, anew software module is simply inserted somewhere before the costing and output procedures. This new module contains the engineering algorithms for the new network architecture, and it computes engineered equipment and facility quantities, just as the previous architecture modules. Because the architecture modules run independently, there are no constraints on the types of new network architectures that can be inserted into the system in this approach.

Separation of the modeling of sites, services, and equipment on the one hand and network engineering on the other enables many new architectures to be added to the system without requiring changes to the structures of the databases or the software that creates them. For all new architectures, new databases must be created, but their structures often remain the same. There are some exceptions, however. For example, attenuation and signal distortions can often be overlooked in engineering fiber systems, but they are critical to the engineering of coaxial systems. Fields describing these parameters can therefore be omitted from the databases for fiber architectures, but the database structures must be expanded to include them when the software system is expanded to engineer coax networks.

SOFTWARE IMPLEMENTATION

The planning and engineering approach described thus far has been implemented at Bellcore in the *Optiaccess* software system, which is described in Fig. 8. This system incorporates several different loop architectures, including fiber-coax, fiber-to-the-curb, fiber-to-the-home, and copper-distribution architectures. These architectures can be used to study many different combinations of voice, data broadcast video, and switched video services. The implementation is also portable, running on MS-DOS®, Macintosh®, and UNIX® computing platforms.

Geographic modeling in a planning and engineering system is an important issue, because one user might want to study broadgauge issues for which an idealized model is sufficient, while another might want to study a particular geographic area in full detail. Our implementation allows users to take either perspective. The system cart construct detailed geographic models for generic urban, suburban, and rural areas in terms of high-level network attributes, such as lot sizes, street widths, number of houses per block, and serving node sizes. Alternatively, planners and engineers can construct geographic models for specific areas by providing precise geographic coordinates and interconnections for every node. Moreover, the two perspectives can be

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Macintosh is a registered trademark of Apple Computer, Inc.
UNIX is a registered trademark of UNIX System Laboratories, Inc.

combined. A sites database defined in terms of high-level attributes can be adjusted at a low level to facilitate the modeling of irregular areas.

Finally, our implementation enables users to take account of several different economic factors. Component costs can be trended using a combination of learning curves and inflation, and users can specify the relationship between volume accumulation for learning-curve-based costs and time for inflation-based costs. Recurring costs, such as maintenance costs for different equipment items and facilities, can also be provided as can revenues. Finally, the system can examine phased deployment in an area over an arbitrary number of years.

SAMPLE RESULTS

Figures 9-12 show some sample application study results that were generated by the *Optiaccess* system. These results included here were selected to illustrate the variety of questions that this approach can be used to study.

Figure 9 graphs a breakdown of installed first costs for two coaxial cable distribution systems, one designed for 550 MHz and the other for 750 MHz. The graph shows that the 550 MHz system has slightly higher cable costs, but fewer amplifiers and a lower cost overall. The graph also suggests that the least-cost coaxial cable distribution design, taking account of the trade-off between cable sizes and amplifiers, depends on the bandwidth for which the system is designed.

To run this study in the *Optiaccess* system, a sites database describing the geographic area and a services database were created. Two equipment databases were used, one specifying the technical characteristics of coaxial cable, amplifiers, splitters, and taps at 550 MHz, the other at 750 MHz. The network evaluation program was run several times with the sites and services databases and each equipment databases, the different runs reflecting various combinations of coaxial cable types for the drop, sideleg, and main cable portions of the network and several arrangements of different numbers of amplifiers. Choices of cable types and amplifiers that did not deliver sufficient signal power to each subscriber were discarded, and the least-cost serving arrangements for both 550 MHz and 750 MHz that did deliver acceptable signals to all subscribers are shown in the figure.

Figure 10 graphs installed first costs as a function of the penetration of a residential switched video service. Four different fiber-to-the-home approaches — one active architecture and three passive architectures — are examined. The graph shows both the economic trade-offs among the architectures (the active architecture is most expensive) and the sensitivities within each architecture to the demand for switched video (cost is most sensitive in the two least expensive passive architectures and least sensitive in the other passive architecture).

This study used a different sites database for each switched video take rate studied, one services database, and one equipment database. The sites databases were identical except in the relative breakdown of residential subscriber sites between two categories, one defined in the services database as subscribing to switched video and the other defined as not subscribing to switched video. The network evaluation program was run with each sites database for each of the four network architectures to compute the cost of each architecture at the take rate modeled in the sites database.

Figure 11 shows a phased deployment study of a fiber-to-the-curb architecture that conforms to [1]. This study compares, for a real-world geographic area, the cost of deploying fiber for the entire area at the beginning of the study period vs. phased deployment over a five-year period. The results show savings in the phased deployment scenario of 26% of subscriber premises costs, 21% of ONU costs, and about 14% of HDT and outside plant costs.

This study used one sites database for each year of the study, reflecting the portion of the network that would be built by that year in the phased deployment scenario. There is also a separate equipment database for each year, reflecting changes over time of unit costs, driven both by learning curves and inflation. To compute the costs of building the entire network at the beginning of the study period, the network evaluation program was given the sites database for the last year of the phased scenario (reflecting the entire area), along with a services database and the equipment database for the first year of the study (reflecting component costs for when the network is deployed). For the phased deployment case, the network evaluation program was given each of the sites databases, along with the services and equipment databases. The network was engineered for each year of the study independently, and the engineered quantities of equipment for each year (except the first year of the study) were diminished by the engineered quantities from the previous year to derive the incremental engineered quantities for phased deployment in the given year. These incremental engineered quantities were multiplied by the unit costs for the appropriate year and then converted to their present value equivalents (a discounting rate of 10% is assumed). The present worths of expenditures (PWEs) in Fig. 10 are the sums of the discounted installed first costs for each year.

Finally, Fig. 12 shows an example of a study that uses the *Optiaccess* system to evaluate networks in non-economic terms. Coaxial cable systems are laid out in a grid model with variable lot sizes, modeling a spectrum of population densities. For both l/2-inch and 3/4-inch coaxial cable, this study examines the maximum number of subscribers that the system can serve without needing additional amplifiers. The data show that the number of subscribers that can be served without amplifiers is roughly inversely proportional to the lot frontages, and the figure suggests that this number is also directly proportional to the diameter of the coaxial cable.

For this study, sites databases reflecting different lot frontages were used, along with a services database and an equipment database, the latter modeling the attenuation of both types of coaxial cable. The network evaluation program was run with each sites database for both types of coax. Instead of engineering and cost output reports, as used in the previous studies, this study examined the signal power levels at subscriber sites to determine how many subscribers received adequate signals.

CONCLUSIONS

Figure 13 summarizes the main conclusions of this paper. We have discussed the new capabilities that are required for a next generation of planning and engineering tools to accommodate emerging local access technologies, architectures, and service demands. New planning and engineering tools must be able to take account of a variety of voice, data and video services, as well as uncertainties about which services local access network providers will offer and uncertain subscriber demands for those services. In addition, these tools must not only handle today's leading-edge technologies and architectures, but must also be extensible to new technologies, architectures, and service demands as they appear.

We have also discussed the *Optiaccess* software system, an implementation that addresses these planning and engineering challenges and incorporates the design approach outlined above. This software demonstrates that the challenges described in this paper can be addressed as planning and engineering systems continue to evolve.

ACKNOWLEDGMENTS

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Bellcore

Bell Communications Research

A New Approach to Network Planning and Engineering

Martin I. Eiger

Planning and Engineering Systems

- **Objectives**
  - **Evaluate network alternatives to decide what networks should be deployed where**
  - **Compare implementations of network or system functions or designs to select best approach**
  - **Investigate new service scenarios**
- **Users**
  - **Local access providers**
  - **Manufacturers**

FIGURE 1

Impact of New Technologies on Planning

- Need to model many new technologies and network architectures
- Increasingly varied service demands
- Uncertainties in future costs, traffic patterns, architectures
- Large number of network options to consider

FIGURE 2

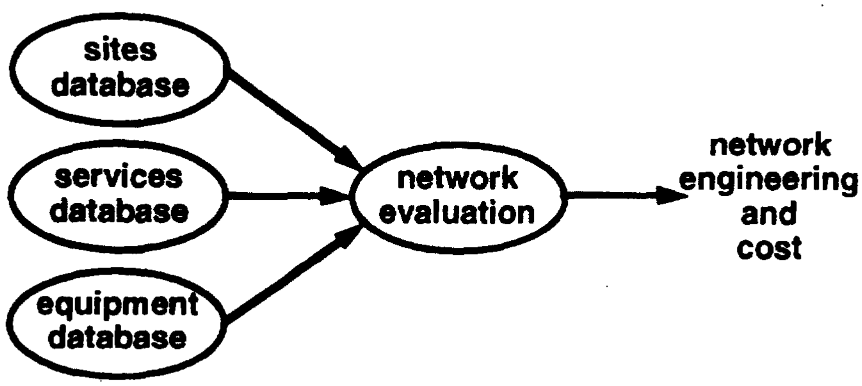
Key Parameters—Examples

- Network architecture
- Population density
- Component costs
- Bit rates/bandwidths
- Topology
- Splitting ratios
- Revenues
- Service offerings
- Peak-hour usage
- Blocking probabilities
- Cost trends
- Technical characteristics (e.g., attenuation, tap loss)

⋮

FIGURE 3

Structure of Solution



- User-populated databases can model many alternatives
- Easy to vary any subset of inputs, run through process several times to study sensitivities, optimize results

FIGURE 4

Evolving Challenge

- Expanding set of architectures: fiber-coax, FTTC, FTTH, ???
- Changing view of offered services, take rates, usage statistics
- Impact of other advancing technologies, e.g., video coding, data compression
- Changing regulatory/business environment

FIGURE 5

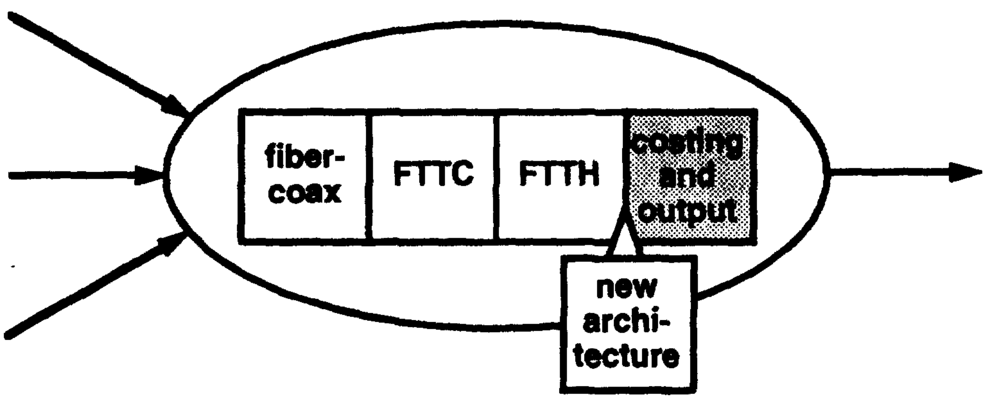
Defining an Architecture for Implementation

- Services or combinations of services that can be accommodated
- List of types of equipment and facilities required to process and deliver signals
- Engineering algorithms for each network node

Inputs	Outputs
Traffic processed	Engineered quantities of equipment
Number of subscribers served	Engineered facilities
Equipment sizes	
Number of incoming cables	
Technical attributes of equipment	
• • •	

FIGURE 6

Incorporating New Architectures



- New architectures reuse existing database structures
- Sometimes database structures must be expanded, e.g., modeling coax attenuation, tap losses

FIGURE 7

Implementation

Optiaccess™ Software System

- Fiber-coax, FTTC, FTTH, copper
- Voice, data, broadcast video, switched video
- MS-DOS®, Macintosh®, UNIX® platforms
- Geographic models
  — built-in urban, suburban, rural rectangular grids
  — real-world user-specified layouts
- Economic factors: learning curves, inflation, revenues, phased deployment

FIGURE 8

Sample Results — Least-Cost Coax Alternatives

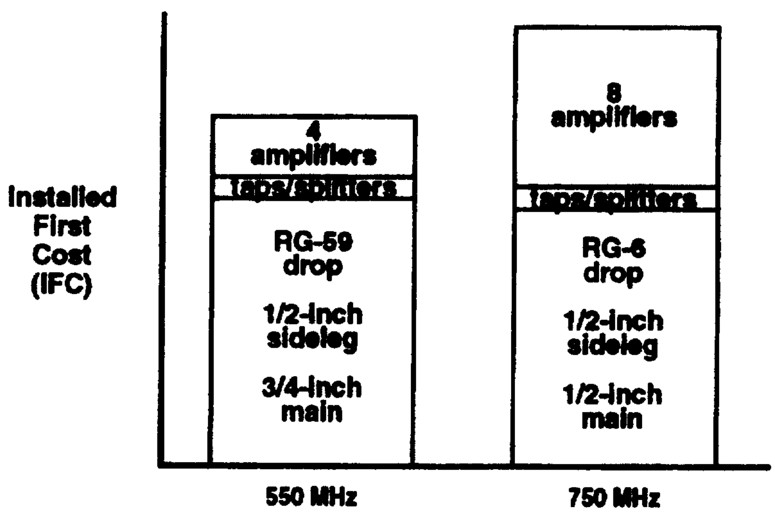


FIGURE 9

Sample Results — Switched Video Costs

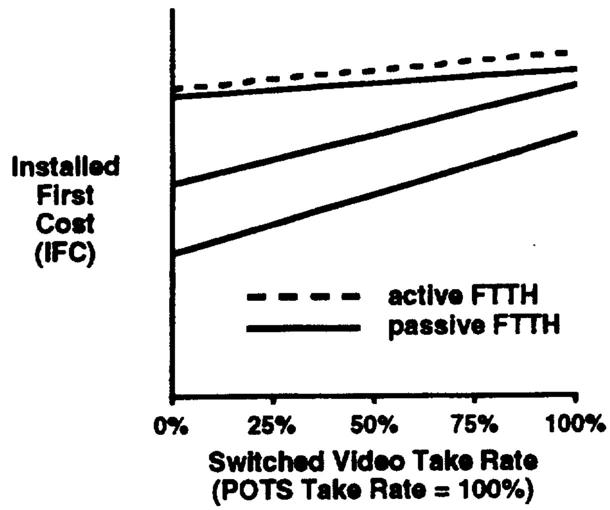


FIGURE 10

Sample Results — Phased FTTC Deployment

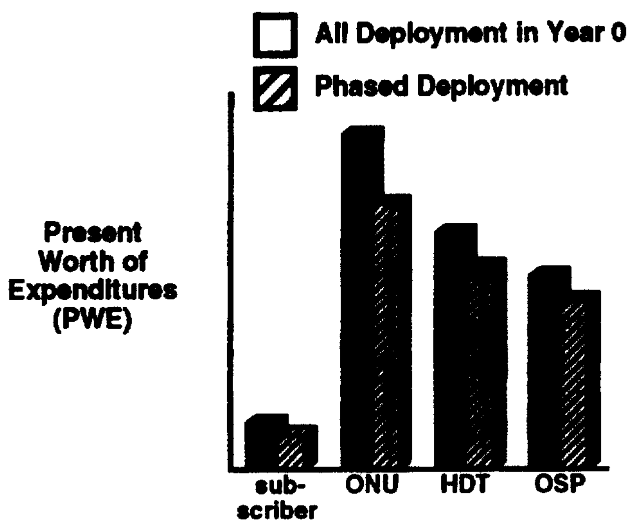


FIGURE 11

Sample Results — Fiber-Coax Subscribers Served

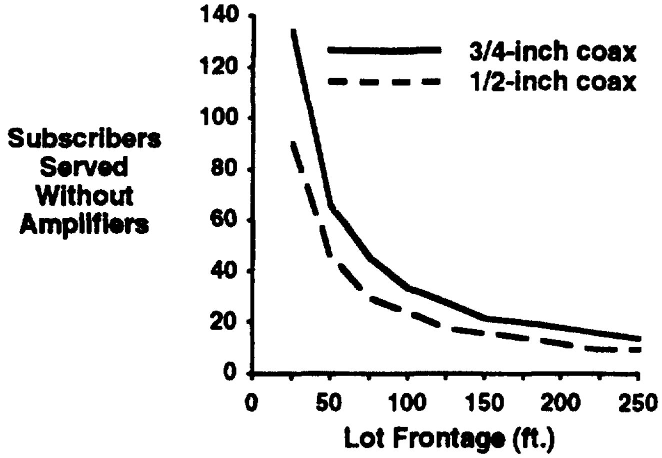


FIGURE 12

Conclusions

- Access planning and engineering for emerging technologies and architectures is different from traditional copper planning and engineering
- New approaches are necessary for the next generation of P&E tools
  - Must handle more complicated architectural and engineering challenges
  - Must provide easy upgrade for new technologies, architectures, and services
- Optiaccess software is an initial implementation addressing new planning and engineering issues

FIGURE 13

AUTOMATED DESIGN OF FIBER-TO-THE-CURB AND HYBRID FIBER-COAX ACCESS NETWORKS

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ABSTRACT

This paper presents two algorithms for automated access network design. An algorithm for fiber to the curb places and sizes ONUs and assigns subscribers to ONUs in a near-optimal configuration for any geographic area and any set of available ONU sizes. The other algorithm, for hybrid fiber coax, selects and places amplifiers, taps, splitters, directional couplers, and cables in the least-cost network configuration that guarantees delivery of signals that meet threshold power levels at arbitrarily many frequencies. Both algorithms have been prototype, and performance results are presented.

1. INTRODUCTION

The fiber-to-the-curb (FTTC) and hybrid fiber-coax (HFC) architectures have received considerable attention in recent years as candidate platforms for emerging local access networks. Both architectures offer the prospect of delivering both narrowband and broadband services at reasonable costs. Many telephone companies have conducted FTTC and HFC trials, and vendors are developing products to facilitate their more widespread deployment.

FTTC features optical fiber transport between a host digital terminal (HDT), which typically serves a few hundred subscribers, and optical network units (ONUs), which serve on the order of 4-16 subscribers. A critical issue in the design of FTTC networks is optimizing the sharing of ONUs among subscribers, which can yield substantial network cost savings. Technical concerns such as signal integrity are important in the metallic drop, but they are less of a network design challenge in the fiber distribution, where there is little signal degradation.

HFC networks, in contrast, use optical fiber only as far as the fiber node, which also serves a few hundred subscribers. Coaxial cable in a tree-and-branch network is then used to connect the fiber node to the subscriber premises. Because coaxial cable is highly attenuative and spans a significant distance, the integrity of signals delivered to subscriber premises is a critical network design issue. A second issue is network economics, which is principally driven by expensive amplifiers to compensate for cable attenuation and splitting losses.

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This paper reports on two algorithms for automated network design, one for FTTC and one for HFC. The FTTC algorithm finds a cost-effective placement of ONUs of various sizes and costs to serve a given area. It uses a branch-and-bound technique and heuristics to find progressively less expensive design solutions, and it also features heuristics for finding progressively higher lower bounds on the cost of the least expensive feasible design. This approach allows network designers to zero in on the least expensive network design satisfying capacity and drop-length constraints, with the algorithm finding progressively narrower upper and lower bounds the longer it is allowed to run (typical run times are on the order of minutes).

The HFC algorithm, in contrast, uses a dynamic programming approach and is guaranteed to find the least-cost network design. It selects splitters, couplers, taps, and cable, and it selects and places amplifiers, so that both forward and reverse signals at arbitrarily many frequencies meet minimum prescribed threshold levels, and so that the cost of the overall network is minimized. The algorithm can also be extended to satisfy policy objectives on amplifier cascades and the relative placement of different types of equipment.

2. ACCESS ARCHITECTURES AND NETWORK DESIGN CHALLENGES

The fiber-to-the-curb and hybrid fiber-coax architectures are shown in Fig. 1. Both architectures feature high-speed transmission over fiber between the central office or head end and a node serving on the order of several hundred subscribers. In FTTC, signals are carried over fiber distribution facilities between the HDT and optical network units and over copper drops between the ONUs and subscriber premises. In HFC, a coaxial tree-and-branch network carries signals between the fiber node and the subscribers.

In FTTC, the HDT and ONU include equipment that converts signals between the optical and electrical domains and that multiplexes, demultiplexes, and grooms electrical signals. The outside plant between the HDT and ONUs is entirely passive, consisting only of fiber, splices, and in some cases, optical splitters/combiners. In HFC, the fiber node also contains equipment that converts between optical and electrical signals and that multiplexes, demultiplexes, and grooms electrical signals. The outside plant, however, includes both passive devices, such as splitters, directional couplers, and taps, as well as active amplifiers that boost signal power levels. These architectures are described in further detail in [1] and [2].

Figure 2 summarizes and contrasts some of the principal design considerations of the two architectures. In the feeder and distribution parts of an FTTC system, signal integrity considerations may limit the number of splices that can be cascaded and the degree of passive splitting that is feasible, but because of the low attenuation of fiber, signal integrity does not otherwise significantly restrict network design. Between the ONUs and subscribers, however, the higher attenuation of the copper media typically requires that drop lengths be sharply bounded. The value of that bound depends on the services being offered and on the specific medium being used in the drop, but it is typically the same for all subscribers, and it constrains where ONUs can be placed.

One network design objective with a significant potential impact on FTTC network cost is increasing the sharing of ONUs. Placing ONUs and defining which subscribers are served by which ONUs in an efficient way reduces the cost of expensive ONU electronics, as well as the number of fibers required in the distribution plant and the matching electronic equipment at the HDT. In addition, if future FTTC systems support traffic concentration at the ONU, larger ONUs will enable more efficient traffic engineering of shared network components. ONU placement and the assignment of subscribers to ONUs is limited, however, by the maximum length of a drop cable.

In HFC networks, signal integrity is a much more critical design consideration, because of the high attenuation of coaxial cable and the high degree of splitting required to transmit a shared signal to many different locations. Amplifiers are used to compensate for these attenuation and splitting losses, but it is important to minimize the number of amplifiers in a network design. Amplifiers add noise and distortion to electrical signals, and they add significantly to the cost of a fiber-coax system.

The design challenges for the two systems are thus significantly different. For FTTC, an important objective is to place ONUs so as to maximize sharing and efficiency, subject to drop-length limitations. For HFC, it is important to design the entire network, which includes selecting and placing amplifiers, passive components, and cable, so that the number of amplifiers is minimized and so that each subscriber still receives sufficient signal power. The following sections describe our approaches to solving these two different problems.

3. FIBER TO THE CURB

Figure 3 presents the ONU placement problem for FTTC. We are given a physical network, which includes a tree whose root node is the HDT, whose leaf nodes are subscriber premises, and whose interior nodes are poles or pedestals at which ONUs can, but need not necessarily, be placed. The tree also includes distances between all pairs of adjacent nodes.

Another input to the ONU placement problem is a description of the available ONUs. Each ONU is characterized by the number of subscribers that it can serve and by its unit cost. Typically, larger ONUs have smaller costs per subscriber than smaller ONUs.

The final input to the problem is the maximum drop cable length. This can be any distance, provided that it is greater than or equal to the largest distance between any subscriber and the pole or pedestal at which it is connected to the network.

A solution to the problem consists of a placement of ONUs on poles and pedestals and a mapping of subscribers to ONUs. Each subscriber may be served by an ONU on the nearest pole or pedestal or on a nearby pole or pedestal on either side of the nearest pole or pedestal. For each subscriber, however, the distance from the subscriber premises to its

ONU must be less than or equal to the upper bound on drop lengths. In addition, each ONU may serve at most as many subscribers as its capacity allows (although more than one ONU may be placed at the same pole or pedestal), Within these constraints, it is desirable to keep costs as low as possible.

Our algorithm for this problem is summarized in Fig. 4. It is not guaranteed to find the absolute minimum-cost ONU placement, but it does find, within about a minute for typical problems (several hundred subscribers), solutions that are provably within a few percent of the least-cost solution, and that may be closer to the optimal solution than that. In many cases, the algorithm finds the provably least-cost configuration of ONUs.

The algorithm consists of three components. One part adapts the algorithm in [3] to find an initial placement of ONUs. This initial phase runs quickly and is guaranteed to be optimal if all subscribers must be served by ONUs of the same size. Then, the algorithm uses local search procedures to find successively lower-cost network designs, taking advantage of the different ONU sizes. For large areas and several available ONU sizes, this could take a long time to guarantee the optimal solution, but in practice it finds good solutions within about a minute.

Another component of the algorithm computes lower bounds on the cost of the optimal ONU configuration. It explores sets of subscribers that are sufficiently far away from each other that they must be served by different ONUs in order to satisfy the drop length constraint. This provides a theoretical minimum value for the number of ONUs that are required in the network, from which a lower bound on the cost of the ONUs in the network can be derived. Heuristic and dynamic programming approaches subsequently refine the lower bound on ONU costs.

The third part of the algorithm takes the least-cost ONU configuration from the first part of the algorithm as input, including the sizes and placement of ONUs and an assignment of subscribers to ONUs. This part of the algorithm does not vary the set of ONUs deployed in a network, and it therefore does not impact the cost of the ONUs in the solution. Instead, it minimizes drop costs by more efficiently mapping subscribers to ONUs and by more efficiently placing ONUs. It does this by solving a network flow problem [4] and by exploring the impact of moving ONUs to adjacent poles or pedestals.

The first and second parts of the algorithm, which compute upper and lower bounds on ONU costs, run first. In our prototype, the user specifies how much time to allocate to each task, and the prototype reports improvements on both bounds as they are derived. After the initially allocated time has elapsed, the user may allocate additional time to either or both tasks (and be reprompted after that time has passed), or the user may move on to the third part of the algorithm, which optimizes ONU locations and drop lengths.

Figure 5 illustrates the processes of computing upper and lower bounds on the ONU cost of the network. These bounds are computed independently, with the user specifying how much time to spend on each bound. The sample problem shown here was chosen for its complexity and includes seven available ONU sizes, 1000 poles, and 2500 subscribers. Despite the size of this problem, the upper and lower bounds converged to about 4% of each other within two minutes.

4. HYBRID FIBER COAX

Because signal integrity is critical and impacts engineering throughout an HFC system, the design of HFC networks is fundamentally different from FTTC design. An HFC design must deliver sufficient signal power to all subscribers, while at the same time minimizing the use of amplifiers, which are expensive and which add noise and distortions. A network design may also be required to satisfy other constraints, such as limits on the number of amplifiers in cascade or the relative placement of different types of equipment or cable.

Figure 6 states the HFC design problem. The geographic input is similar to the geographic input for FTTC. It consists of a tree whose root is the fiber node, whose leaves are subscriber premises, and whose interior nodes are again poles or pedestals. The geographic input also includes distances between adjacent nodes.

The other input to the HFC design problem is a list of all equipment and cable that is available to be deployed in the network. This includes network interfaces, taps, amplifiers, splitters, directional couplers, coaxial cable, and launch amplifiers. Each object is characterized by its unit cost, and coaxial cable is characterized by its cost per unit length. Taps, amplifiers, and splitters are also characterized by their branching degrees (number of subscribers per tap, number of outputs per splitter or amplifier). Finally, all objects and cable are described by their technical attributes. These attributes vary from one category of object to another, and are detailed in [5]. They include input power thresholds, output power levels, losses, gains, and attenuation per unit length. Each attribute for each object or cable type can be specified for any number of signal frequencies.

The output of the algorithm is a complete network design. Equivalently, it is a mapping from each node in the network to the equipment deployed at that node, if any, and from each cable span to the cable type deployed along that span. The network design is guaranteed to provide sufficient signal power levels to every subscriber at every frequency for which technical attributes are provided in both the forward and reverse directions. Subject to these constraints, the algorithm finds the least-cost feasible network configuration.

The algorithm treats each node in the network as a deployment decision, where the set of options is determined by the branching degree of the node and by its location relative to the subscribers and the fiber node. The algorithm considers all available network interface objects for each subscriber, all taps with sufficient branching for tap nodes, and all amplifiers, splitters, and directional couplers with sufficient branching for interior branching nodes. For interior nodes with no branching, the algorithm considers both amplifiers and the option of deploying nothing. Finally, for each cable span, the algorithm considers all types of available cable, either drop cable for spans between subscriber premises and taps or distribution cable for spans between taps and the fiber node.

The algorithm evaluates the feasibility and cost of every deployment option, and it uses a dynamic programming approach to guarantee that the network design that it computes is the feasible design of minimum cost. Unlike the FTTC algorithm, the HFC algorithm does not compute successively better solutions; rather, it finds only one solution. However, this design is guaranteed to minimize not only the total number of amplifiers, but also the total cost of the network.

Figures 7 and 8 present some run-time statistics of this algorithm. In Fig. 7, we examine a baseline scenario with 120 subscribers, 1 cable choice per span, 10 tap choices, and 1 frequency being monitored. Then, for each of these four variables, we fix three and vary one, with run times as shown in the figure. Figure 8 is similar, but with a baseline scenario of 480 subscribers, 1 cable choice, 20 tap choices, and 6 frequencies.

The data shown in these figures suggest that the algorithm runs on the order of a few seconds to a few minutes for most of the cases studied. The data also suggest that the run time is dominated by terms that are linear or sublinear in each of the four parameters studied. The only case where run time is slower than a few minutes is when the number of cable types is greater than 1. This represents a case of little practical interest, however, because in this case the algorithm treats every cable span as an independent deployment decision. In practice, it is likely that only one type of cable will be used in a given area, or that one type of cable will be used from the fiber node to some point in the field, and another type of cable will be used from that point to the taps. With these limitations, the run time of the algorithm would be only a small multiple of the run times shown in the graphs.

Finally, Fig. 9 shows some enhancements to the algorithm that would enable users of the algorithm to specify additional types of design feasibility constraints. The algorithm can easily be adapted either to require particular deployment choices at specified nodes (preplaced equipment) or to forbid specific deployment options. The algorithm can also be expanded to constrain the number or types of amplifiers in cascade between the fiber node and subscribers, or to constrain the relative positioning of equipment and cable along a path from the fiber node to subscribers. This extension may increase the run time of the algorithm, where the increased run time would be related to the complexity of the constraints. The algorithm can also be extended to guarantee carrier-to-noise ratio (CNR) and distortion thresholds, in addition to the signal level thresholds that it presently guarantees. Finally, we are exploring how to extend the algorithm so that it can engineer backfeeds and parallel cables where they would reduce the cost of the network. This problem is under study, and while we believe that the algorithm can be extended to accommodate parallel cables, it is not clear how this will impact the run time of the algorithm.

5. CONCLUSIONS

The algorithms presented in this paper automate the engineering of fiber-to-the-curb and hybrid fiber-coax systems, taking into account both technical and economic network design objectives, as summarized in Fig. 10. The FTTC algorithm places and sizes ONUs in a near-least-cost configuration, subject to limitations on drop-wire lengths; the algorithm finds progressively lower-cost arrangements of ONUs as it is given more time to run. The HFC algorithm, in contrast, selects and places all equipment and cable in a network area, computing the least-cost design that meets signal delivery objectives at arbitrarily many frequencies in both the forward and reverse directions. Both algorithms can be applied to any geographic area and with any set of equipment and cable specifications.

These algorithms are being incorporated into software products, and work is underway on adding new computational and user-interface features to make them more versatile and more useful to planners and engineers. These algorithms should enable planners and engineers in the future to design less costly access networks more quickly than is possible today, with no compromise in the technical integrity of the designs.

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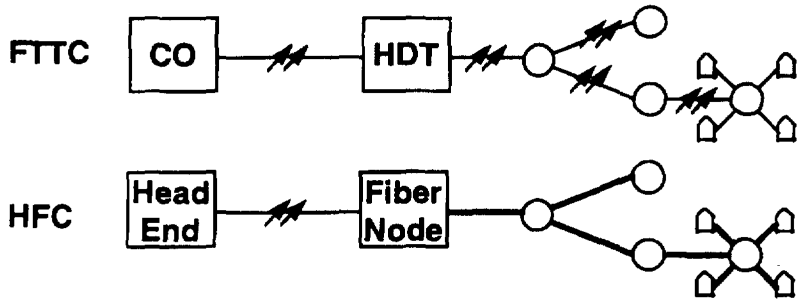
Network Architectures



- High bandwidth for voice and video services
- Relatively inexpensive

FIGURE 1

Network Design Drivers

	FTTC	HFC
signal integrity	limits drop lengths limits splices and optical splitting	critical • coax attenuation • splitting losses • amplifiers add noise and distortions
cost	minimize by efficient assignment of ONUs	minimize by reducing amplifiers

FIGURE 2

FTTC Design Problem

<u>Input</u>

- Physical network (subscriber premises, poles, fiber node, connectivity, distances)
- ONU sizes and costs
- Maximum drop length

<u>Output</u>

- Placement of ONUs
- Mapping from subscribers into ONUs such that
  - Drop lengths are bounded
  - Cost is minimized

FIGURE 3

FTTC Design Approach

- Optimize ONU costs
  - Initial solution computed quickly
  - Successive refinements; longer run times $\rightarrow$ better solutions
  - Lower bounds on cost guarantee quality of design
- Optimize drop costs
  - Adjust placement of ONUs
  - Network flow algorithm guarantees optimal mapping of subscribers to ONUs

FIGURE 4

FTTC Performance

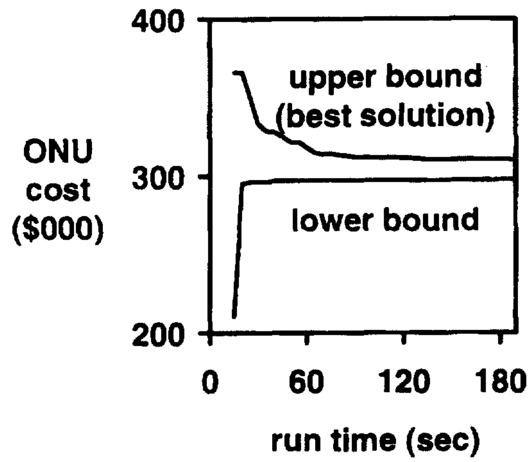


FIGURE 5

HFC Design Problem

Input

- **Network topology (subscriber premises, poles, fiber node, connectivity, distances)**
- **List of available equipment and cable with signal attributes and costs**

Output

- **Mapping from nodes to equipment and cable spans to cable such that**
  - **Design meets signal delivery objectives, possibly other constraints**
  - **Cost is minimized**

FIGURE 6

Run Times

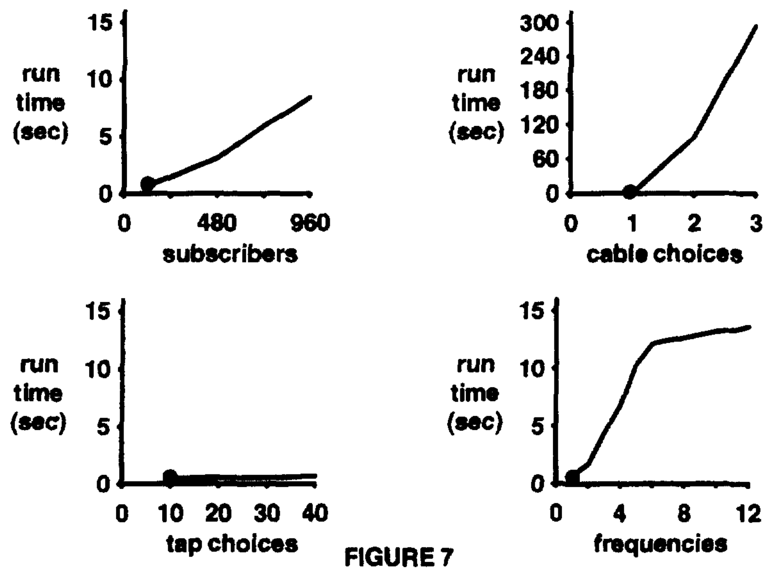


FIGURE 7

Run Times

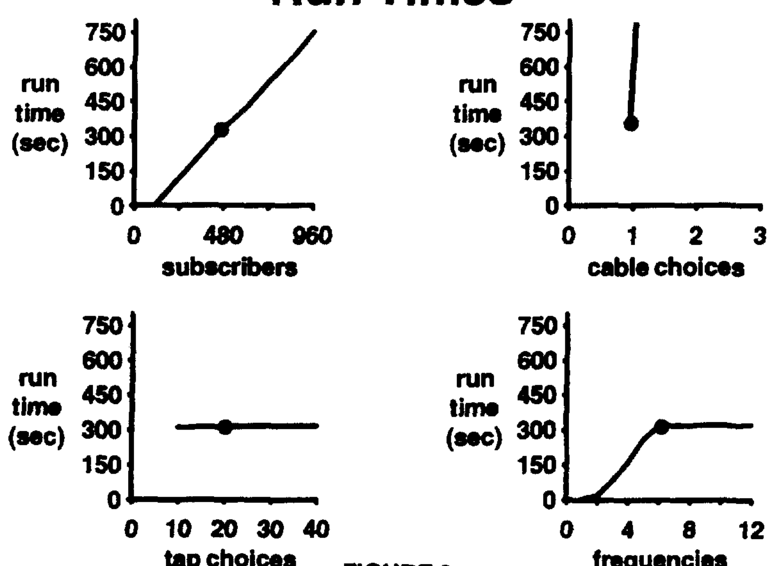


FIGURE 8

HFC Enhancements

- Preplaced and forbidden equipment
- Amplifier cascades
- Relative positioning of equipment and cable
- CNR and distortion thresholds
- Backfeeds/parallel cables

FIGURE 9

Conclusions

- FTTC and HFC network design problems are fundamentally different
  - FTTC: assign ONUS efficiently subject to drop length limitation
  - HFC: guarantee signal levels to all subscribers
- FTTC algorithm places and assigns ONUs; lower costs with longer run times
- HFC algorithm guarantees least-cost network design
- Enhancements for both algorithms underway

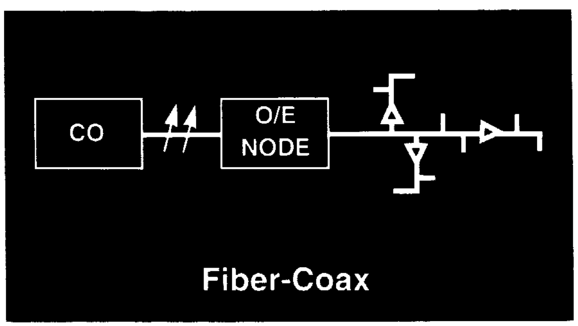
FIGURE 10

*What is the **Optiaccess** system?*

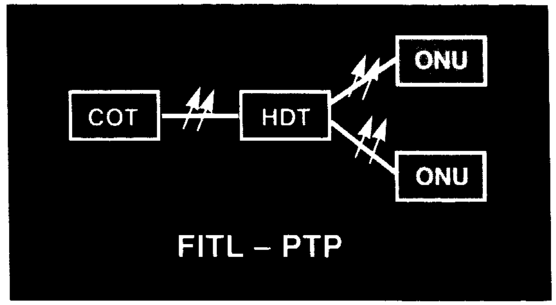
The ***Optiaccess*** system is software that engineers and performs cost analyses for complex broadband access networks, services, and technologies.

*What can I use the **Optiaccess** software system for?*

You can use the ***Optiaccess*** software system for a wide variety of engineering and economic studies and optimizations of fiber-based or hybrid access networks. These can include comparisons of architectures, economic sensitivities from one geographic area to another, and incremental cost analyses for service evolution.



Fiber-Coax



FITL – PTP

*What kinds of local access architectures are included in the **Optiaccess** software system?*

The ***Optiaccess*** system supports all-analog, all-digital, and hybrid fiber-coax architectures, as well as several fiber-to-the-curb approaches, including TR-909 point-to-point and point-to-multipoint topologies. Potential video upgrades to fiber to the curb are also implemented. In addition, the ***Optiaccess*** software system supports broadband fiber to the home based on time-division multiplexing, wavelength-division multiplexing, and passive power splitting.

*What geographic areas can I study with the **Optiaccess** software system?*

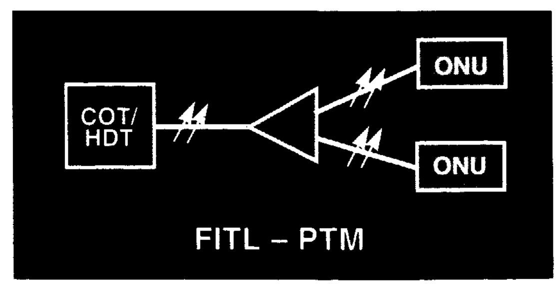
An interactive database editor permits users to lay out their own distribution areas or carrier serving area models. Alternatively, users can select from built-in geographic models representing typical urban, suburban, and rural distribution areas.

*What services can the **Optiaccess** software system analyze?*

The ***Optiaccess*** software system can examine many combinations of voice, data, and video services. The user is prompted to interactively define characteristics of services to be transported, including bit-rates or bandwidths, service penetrations, and usage parameters such as calling rates and peak traffic. The user can also assign different services to different categories of subscribers (e.g., residence, small business, large business).

*What economic measures are available in the **Optiaccess** software system?*

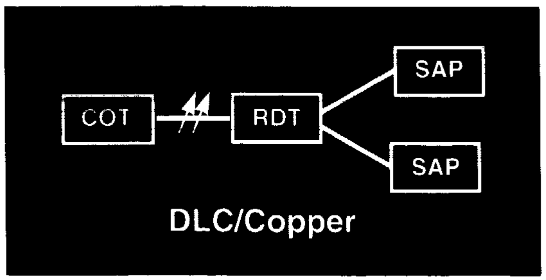
The ***Optiaccess*** software system currently analyzes installed first costs for one-time or phased-deployment studies. At the user's discretion, the ***Optiaccess*** software system can incorporate learning curves and inflation-based cost trends. In the future, ***Optiaccess*** software will incorporate additional economic measures and analyses.



FITL – PTM

*Will the **Optiaccess** software run on my computer?*

The ***Optiaccess*** software system is available for personal computers running the MS-DOS® operating system, Macintosh® computers, and Sun Workstation®, DECstation™, VAX™, and Pyramid computers running the UNIX® operating system.



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